Assessment of Power Conversion and Energy Storage Technologies for Future Space Science Missions

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Jet Propulsion Laboratory

Space Power Workshop

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Outline

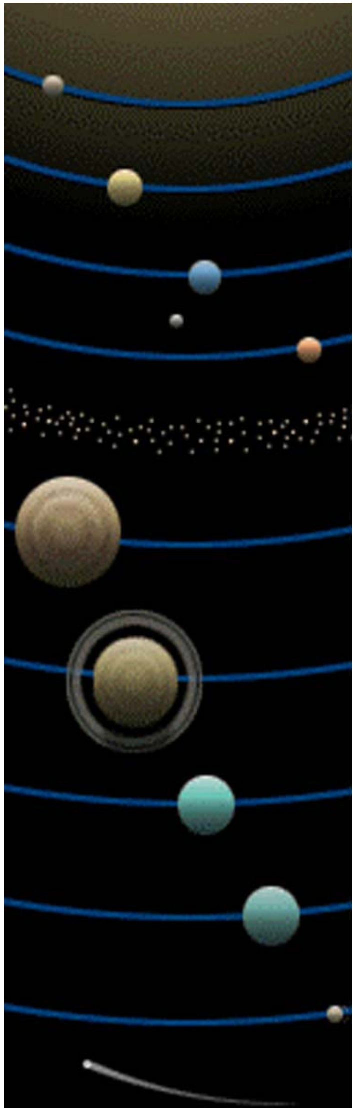
- Background
- Radioisotope Power Source Technology
- Solar Cell and Array Technology
- Energy Storage Technology
- Summary

Power Technology Study Objectives

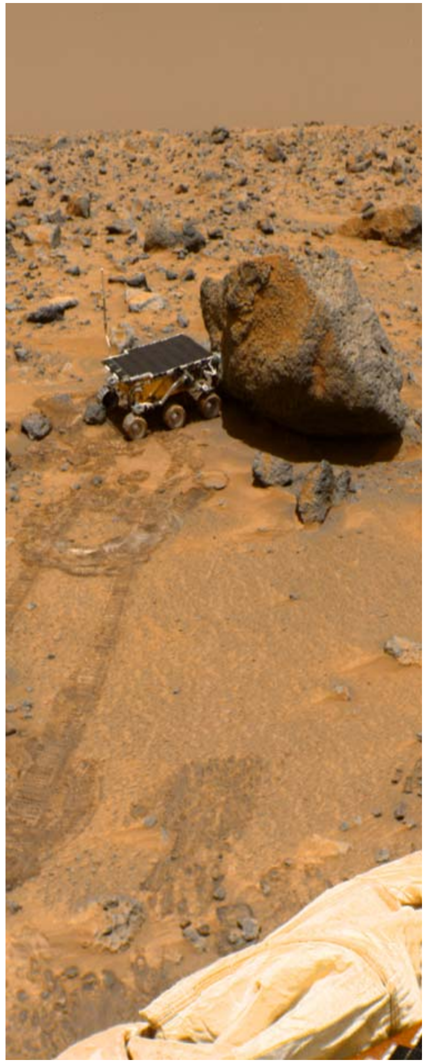
- NASA-Code S requested JPL to assess and identify advanced power source and energy storage technologies needed to enable and enhance the capabilities of future NASA Space Science missions (beyond 2010)
  - Radioisotope Power Source Technologies
  - Solar Cells/Arrays
  - Energy Storage Technologies
- Recommend technology programs that are critical for future NASA Space Science missions and prepare technology road maps and investment strategies.

The assessment studies have been co-sponsored by the Director for Technology, Office of Space Science, the Solar System Exploration Division and the Mars Exploration Program.

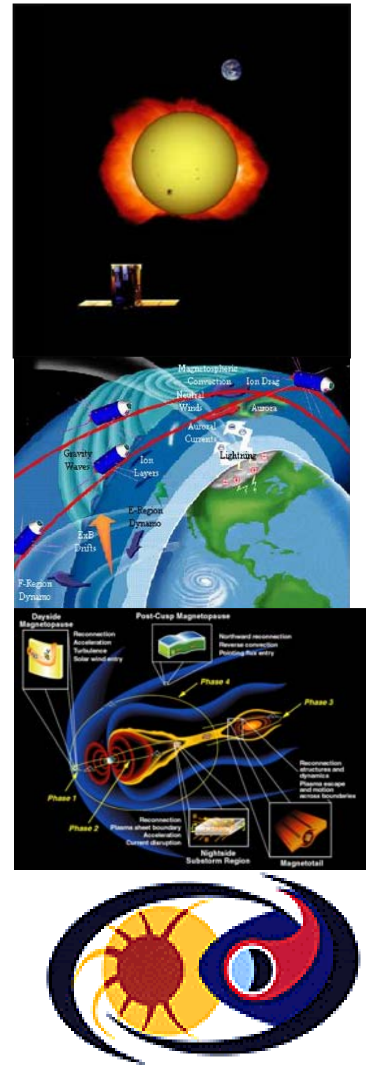
Space Science Missions



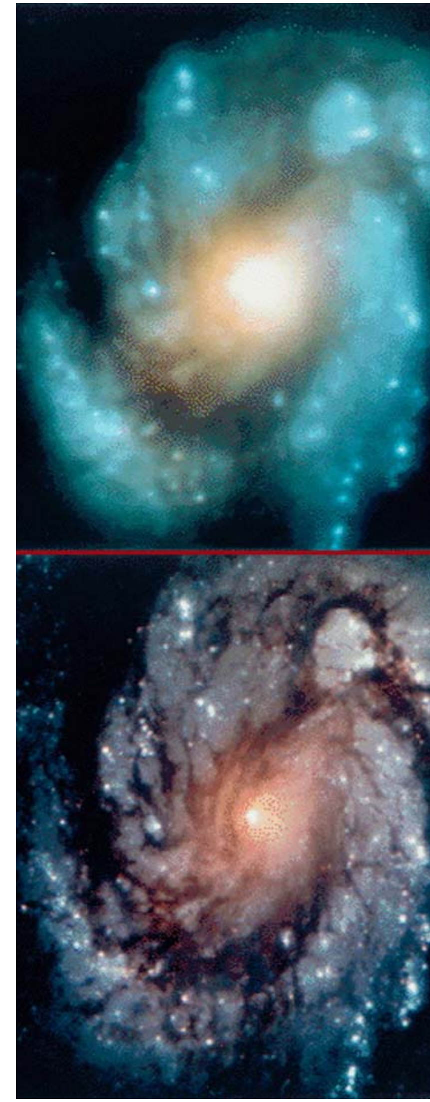
Solar System



Mars Exploration

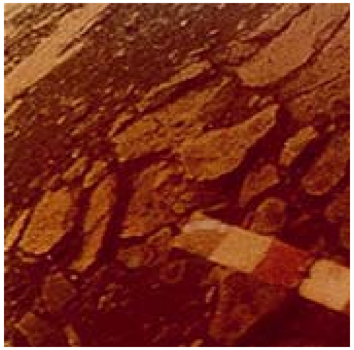


Sun Earth Connection



Origins

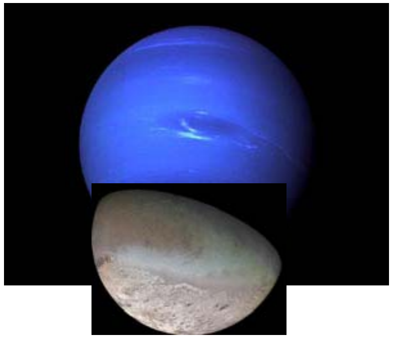
Solar System Exploration Mission Concepts- Far Term



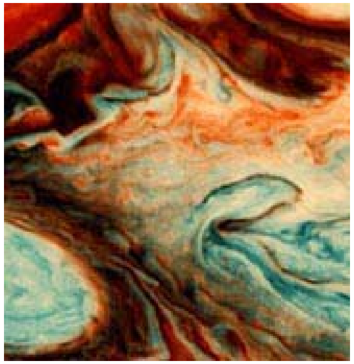
Venus Sample Return

Europa Surface and Subsurface

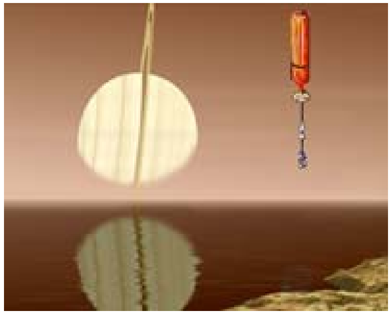
Comet Nucleus Sample Return



Neptune/Triton Orbiter

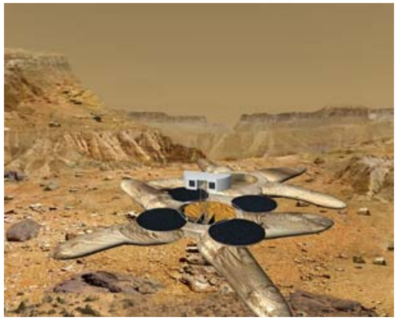


Giant Planet Deep Probes



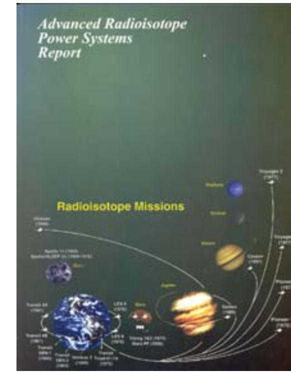
Titan Organic Explorer

Mars Exploration Mission Concepts- Far Term



Power Technology Assessment Status

Power Technology	**Status**
Advanced Radioisotope Power Systems (RPS)	Completed - Report published in June 2001- Report #JPL D-20757
Solar Cell and Array Technology	Completed -Report published in December 2003 Report #JPL D-24454, Rev. A
Energy Storage Technologies	Completed –Report published in March 2005

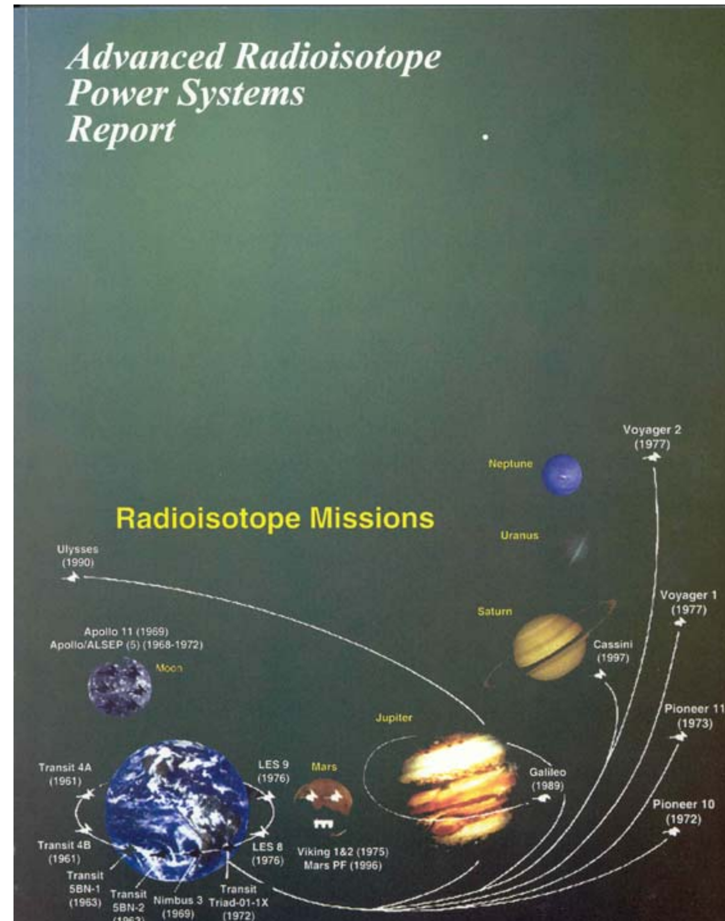


Energy Storage Technology for Future Space Science Missions

Assessment of Advanced Radioisotope Power System Conversion Technologies

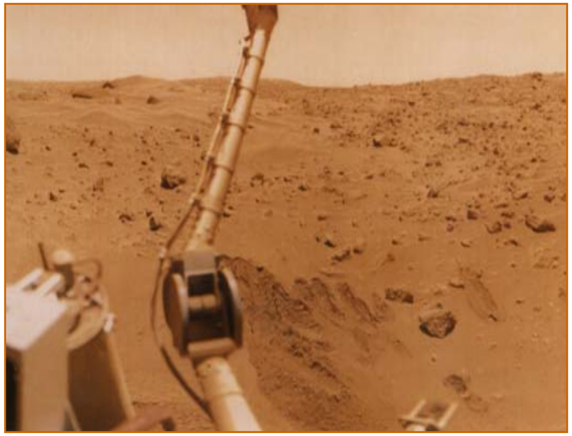
Advanced Radioisotope Power System Conversion Technologies Review Team

- **Rao Surampudi, JPL, Chairperson**.
- Lisa Herrera, DOE
- Bob Carpenter, OSC (DOE support contractor)
- Robert Wiley, BA&H (DOE support contractor)
- Lee Mason, GRC
- Mohamed El-Genk, UNM
- Jack Mondt, JPL
- Donald Rapp, JPL
- Bill Nesmith, JPL

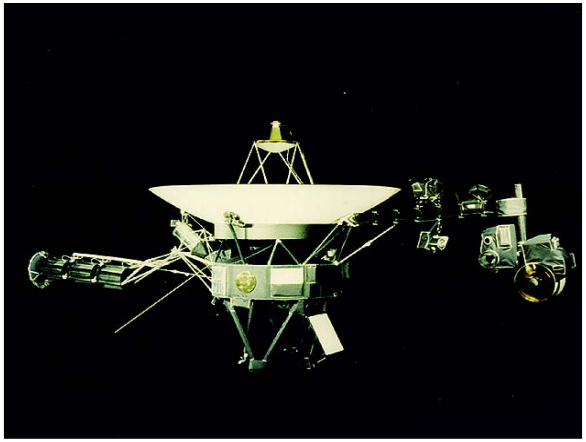


Past NASA Missions Using RPS – Including Moon and Mars

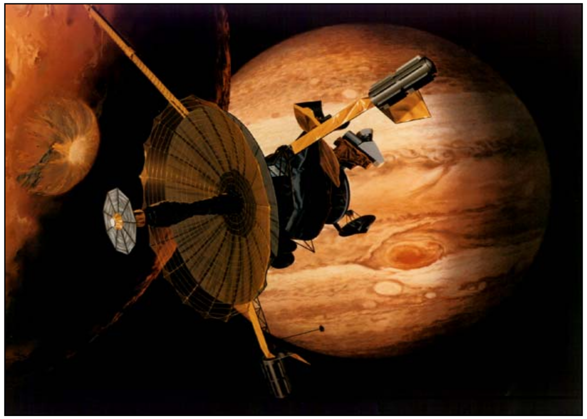
Apollo



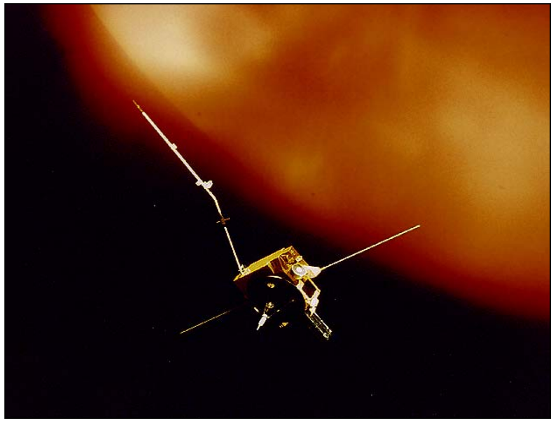
Viking



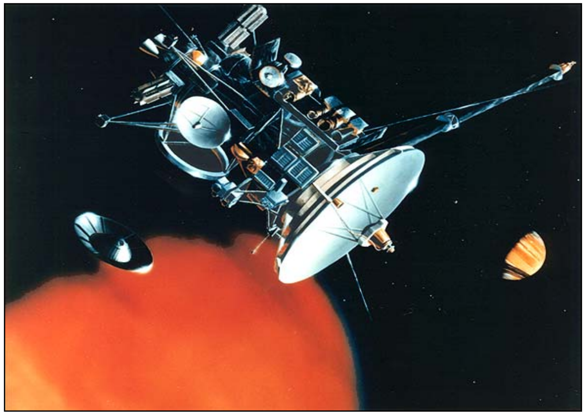
Voyager



Galileo



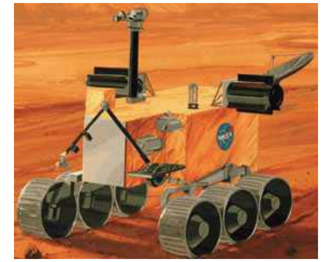
Ulysses



Cassini

Since 1961, 40 RTGs have been used on 22 US space systems.

Potential Future RPS-Powered Missions

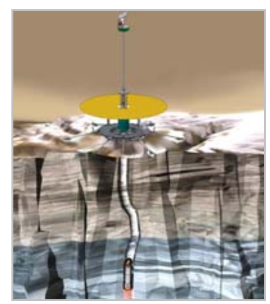
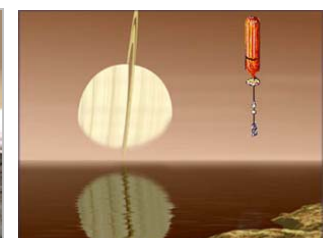




Near-term (2006 to 2015)

- Pluto-Kuiper Belt Explorer (launch ~2006)
- Mars Science Laboratory (launch by 2009)
- 2nd New Frontiers Mission (launch by 2010)
- Mars Scout Missions (launches 2011 & 2015)
- Solar Probe (launch ≥2012)

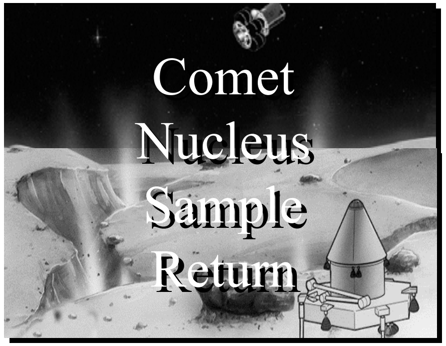
Vision Missions (≥2015)

- Medium Size (New Frontiers)
  - *Trojan/Centaur Reconnaissance Flyby*
  - *Asteroid Rover/Sample Return*
  - *Io Observer*
  - *Ganymede Observer*
- Flagship Class
  - *Europa Lander*
  - *Titan Explorer*
  - *Neptune-Triton Explorer*
  - *Uranus Orbiter with Probes*
  - *Saturn Ring Observer*
  - *Venus Sample Return*
  - *Mercury Sample Return*
  - *Comet Cryogenic Sample Return*
  - *Interstellar Probe*

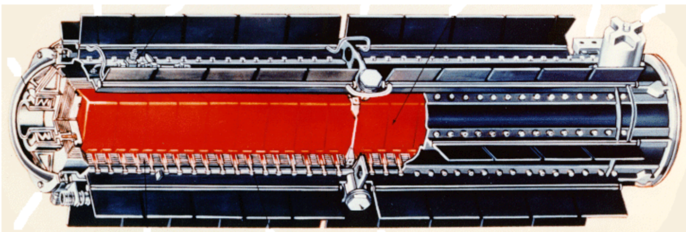



Summary of Future Mission Needs For Radioisotope Power Systems

- Need 100 Watt Class RTG Modules
  - Future missions are smaller in size and require lower power
- Low Mass
  - High Specific Power 8-10 W/kg (2 X SOA SiGe RTGs)
- High Efficiency 13-25 % (2-4 X SOA SiGe RTG's)
  - Uses Less Radioisotope Material
- Long Life
  - 14 Years - Enable Deep Space Missions
- Low EMI & Vibration
  - Enable use of High Precision Cameras and Magnetometers
- Function in CO_2 and other planetary Atmospheres
  - Enable Long Duration Mars and other planetary surface missions (> 2 earth years)



SOA Radioactive Power Source Characteristics of SOA GPHS- RTG



Performance Characteristics

- Power: 285 W (BOL)
- Mass: 56 kg
- Efficiency: 6.5%
- Specific Power: 5.1 W/kg
- Life:> 20 years demonstrated
- Hot Side Temp. :1273 K
- Cold Side Temp.:573 K

Advantages

- Long operational life
- High reliability

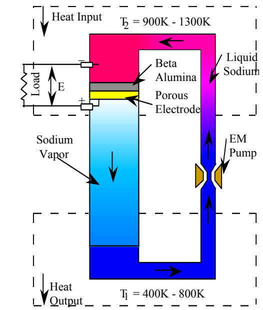
Limitations

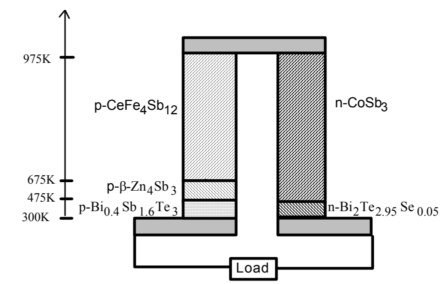
- Low Specific Power
- Low Efficiency (Requires more Pu)

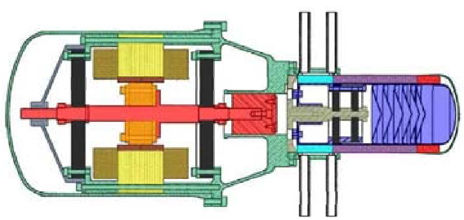
Advanced RPS Technologies

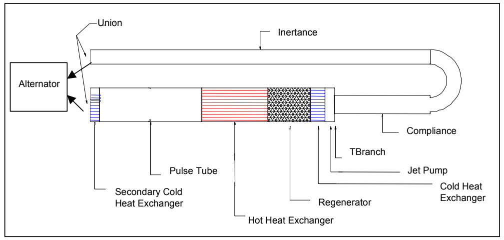
- Alkali Metal Thermal to Electric (AMTEC)
- Advanced Thermoelectric (TE)
- Advanced Stirling Engine Converter (SEC)
- * Thermal Acoustics (TA)
- * Thermionics (TI)
- * Thermophotovoltaics (TPV)

* Early stages of Development

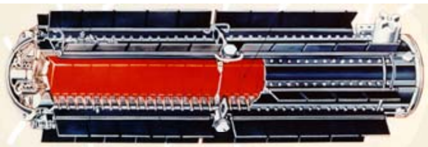




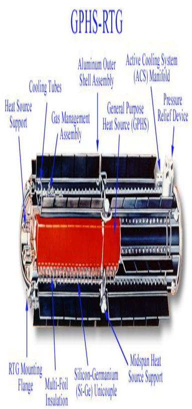




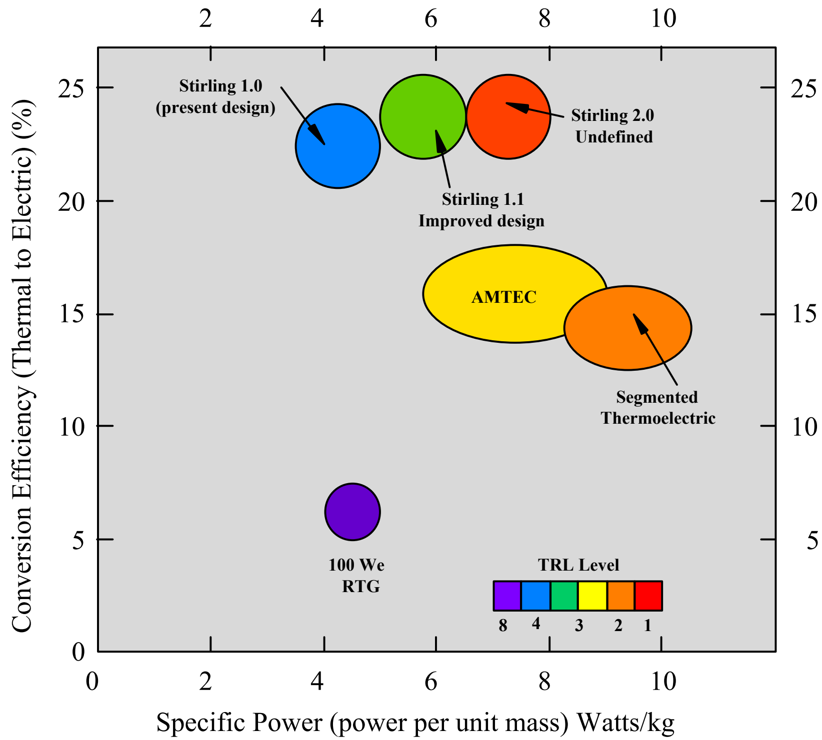
Performance Characteristics of Advanced Radioisotope Power Sources

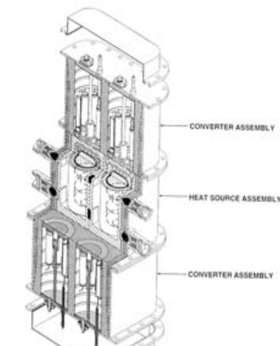


285 W GPHS RTG

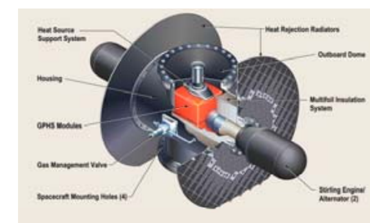


100 W STC





100 W AMTEC



100 W SEC

Characteristics*	Si-Ge RTG	STEC	AMTEC	SEC(1.0)	SEC(1.1)	SEC(2.0)
Hot Temperature (K)	1273	1200	1150	920	920	920
Cold Temp(K)	573	500	600	350	350	350
Efficiency (%)	6.5	15	16.2	23	25	25
Specific Power (W/kg)	4.5	10.2	8.8	4.1	6.0	7.5
System Mass (100 W)	31.2	14	13.6	27	20	16

STC, AMTEC and SEC can be designed to function in both deep space vacuum and planetary environments

Recommendations

NASA to initiate a program to develop Advanced-Stirling, AMTEC and Segmented -TE converter technologies for missions beyond > 2010.

- Establish performance gates and monitor technology progress by the same independent review board
- Down select after two to three years the most promising technologies that meet the requirements for the greatest number of future NASA ESS, SEC and MEP missions.
- Develop selected converter technologies to TRL 5
- Develop advanced radioisotope power system from TRL 5 to TRL 6 with funds from flight project to meet its specific requirements.

Solar Cell and Array Technology Assessment

Solar Cell and Array Technology Assessment Review Team

NASA-JPL
- **Rao Surampudi– Chairman**
- Donald Rapp
- Paul Stella/ Nick Mardesich
- Bill Nesmith

NASA GRC
- Sheila G. Bailey
- Henry B. Curtis
- Mike Piszczor,

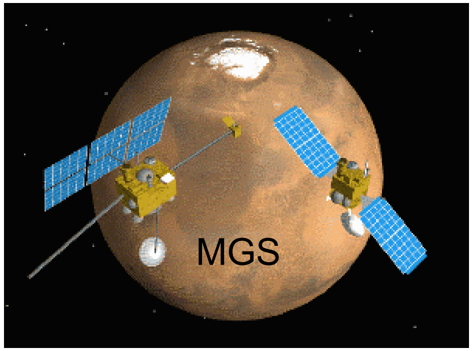
NASA-GSFC
- Ed Gaddy,

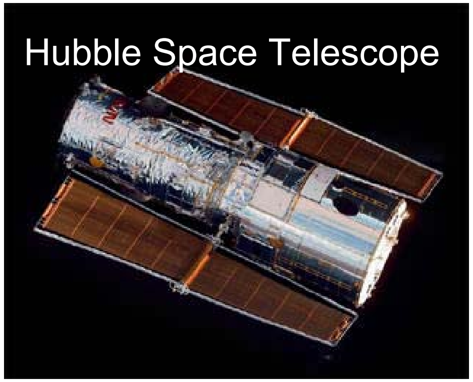
DOD/DOE
- Dean Marvin, Aerospace Corp.
- Larry Kazmerzki, DOE-NREL

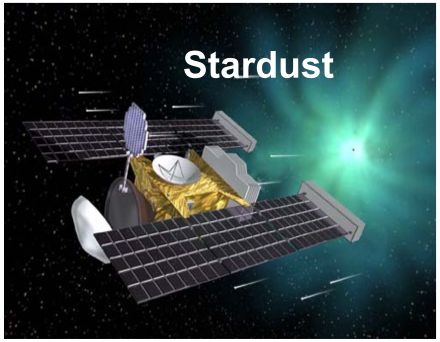
Applications of Photovoltaic Power Systems

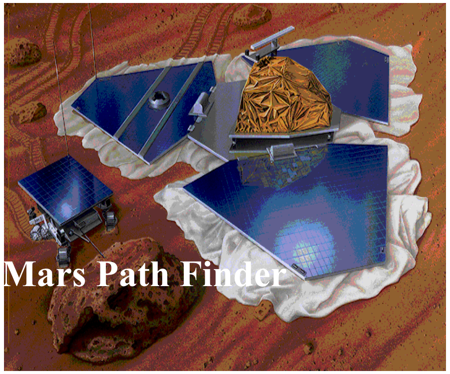
Used on several space science missions launched to date:

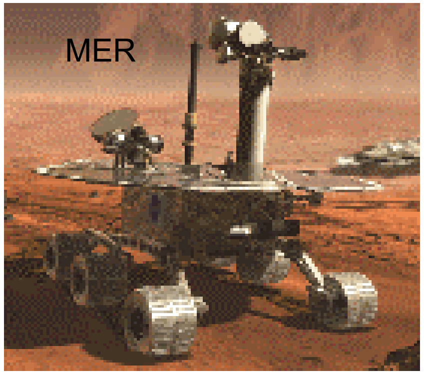
- Near sun: Venus, Mercury…
- Outbound: Mars, Asteroids…
- Earth: Earth observing
- SEP: Deep Space 1…
- Surface: MERs, Pathfinder



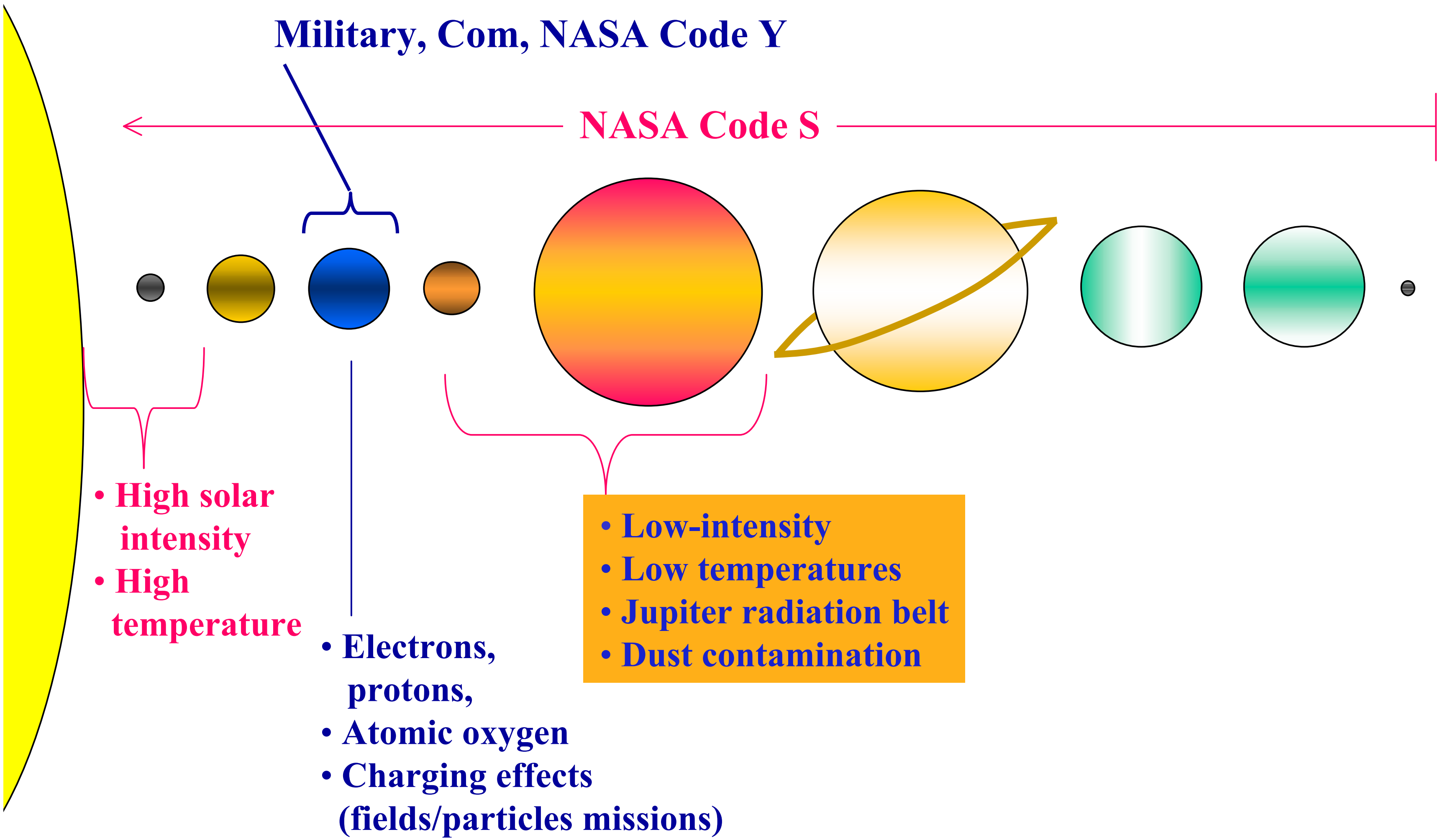






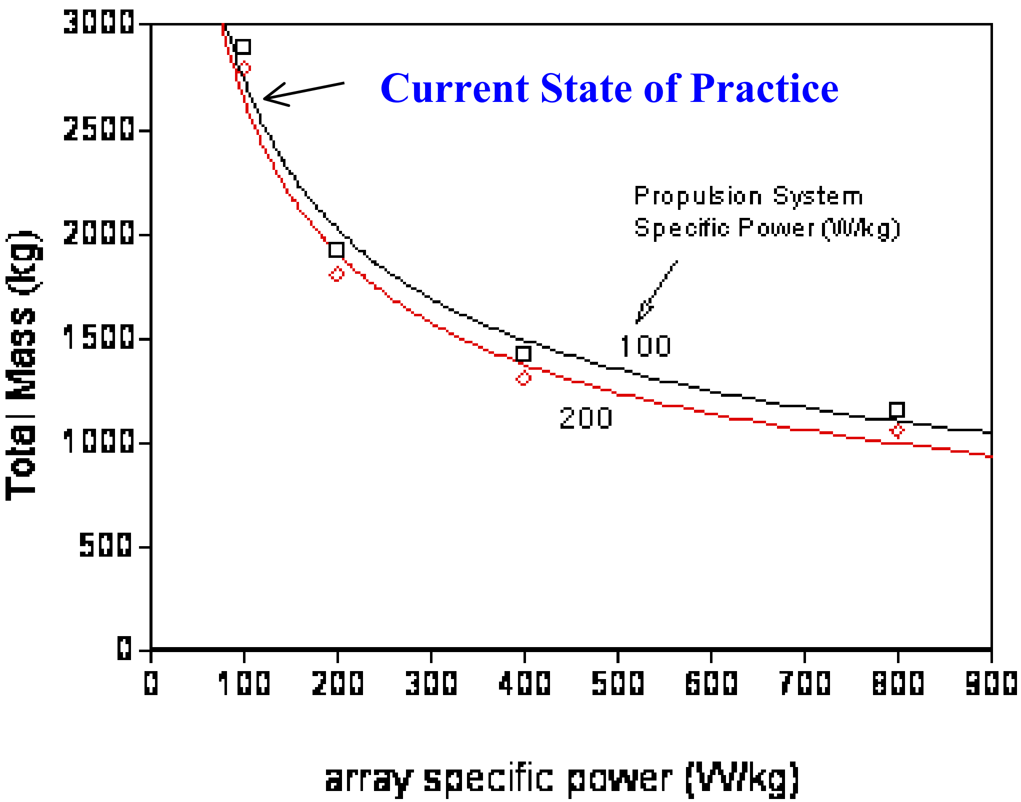


Solar Array Environments for Code-S Missions



Unique Capabilities Needed for SSE Missions SEP to Comets and Asteroids

High array specific power reduces total spacecraft wet mass



Unique Capabilities Needed:

Arrays with:

- High power scalable to ~ 80 kW
- High Voltage
- High Specific Power (> 400 W/kg)
- Low Cost – $ 0.5M /kW
- LILT Performance to 5 AU

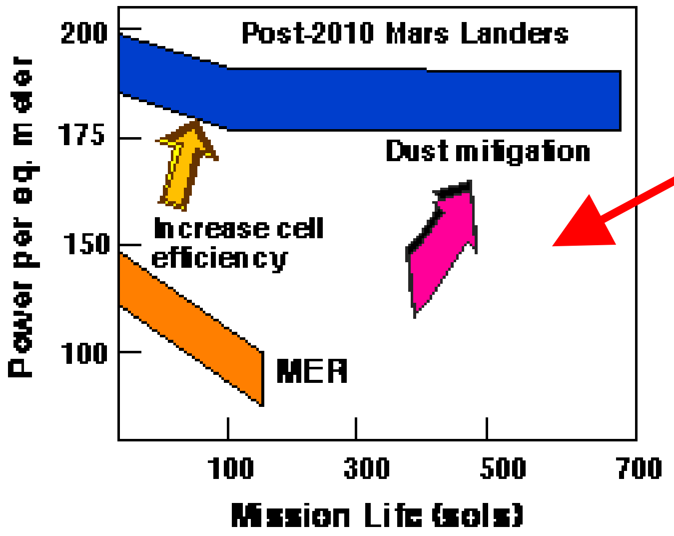
Current State of Practice

- Power ~ 7 kW
- Voltage ~ 100 V
- Specific Power ~ 100 W/kg
- Cost ~ $2M/kW
- LILT to 2 AU

Solar Array Needs for Mars Exploration
Mars Surface Missions

SOLAR ARRAY POWER DENSITY

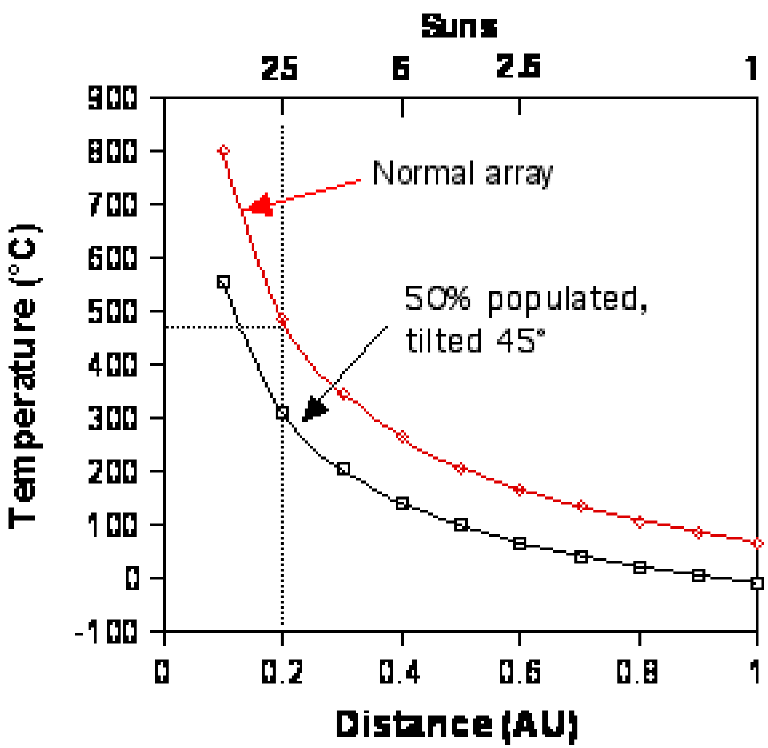
- Solar array area on rovers is very limited
- High power density (W/m^2) is critical need
  - Currently 130 W/m^2 in 2003
  - Need 220 W/m^2 by 2010



EXTENDED OPERATING LIFE

- Need extended operating lifetime capability of solar arrays in dusty environment
  - Currently 90-100 sols
  - Need is > 670 sols (1 Martian year)

Solar Array Needs for SEC Near-Sun Missions
High Temperature Arrays



Array reaches ~ 450°C at 0.2 AU

SEC Theme Plans Near Solar Missions

Mission	Priority	Suns	Year
Current SOA	---	10	2003
Sentinels	enhancing	1 - 11	2008
Telemachus	enhancing	.03 - 25	2010
Telemachus	enabling	1 - 25	2010
PASO	enabling	1 - 35	2015

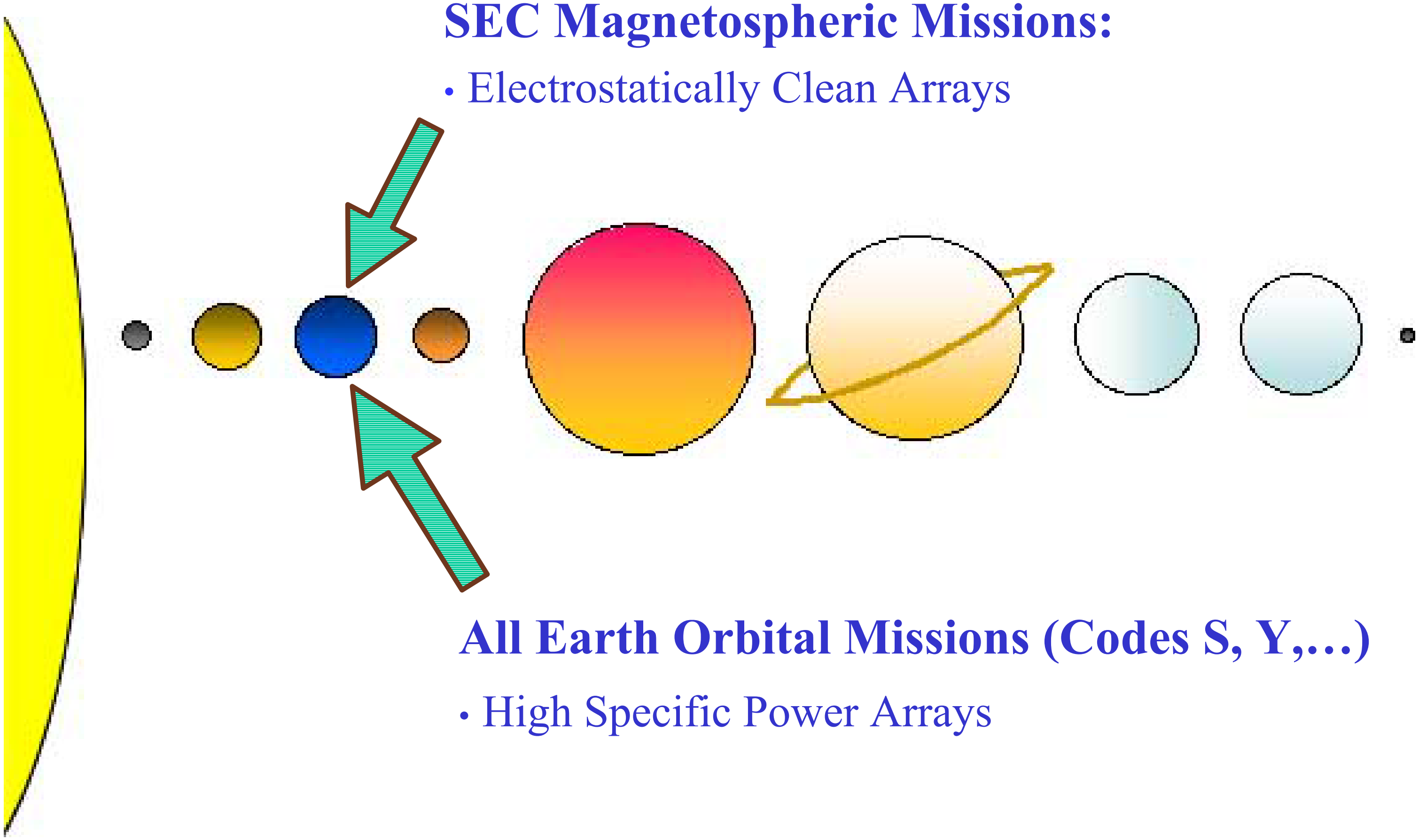
Need:

- Operate at 0.2 AU or less
- Operate at 400 to 450 °C
- Additional benefit for LILT tolerance

Current SOA:

- Partly fill array with reflectors, tilt from sun
- Operate at 120°C at 0.3 au
- Vulnerable to loss of attitude control
- Reduced power level

Solar Array Needs for Earth Orbital Missions



SEC Magnetospheric Missions:

- Electrostatically Clean Arrays

All Earth Orbital Missions (Codes S, Y,…)

- High Specific Power Arrays

Unique Solar Array Needs for Space Science Missions

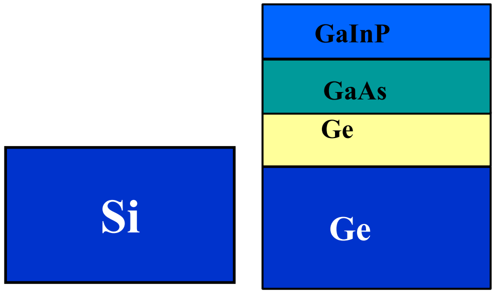
- **Solar System Exploration Program**
  - Driving Missions: Comet and Asteroid and Outer Planetary Missions using Solar Electric Propulsion
  - Unique Needs
    - High power and low cost solar arrays
    - High specific power (watts/kg) arrays
    - Solar arrays that can operate in Low Intensity & Low Temperature (LILT) conditions
- **Mars Exploration Program**:
  - Driving Missions: Mars Surface Missions
  - Unique Needs
    - Arrays with high power per unit area (watts/m^2)
    - Long-life arrays in the dusty environment
- **Sun-Earth Connection Program**
  - Driving Missions: Near-Solar Missions (Telemachus, PASO, Sentinels),
  - Unique Needs
    - Arrays that can operate at solar fluxes
    - Arrays that can function at high and low solar fluxes
- **Earth Orbital Missions**
  - High Specific Power Arrays
  - Electrostatically Clean Arrays

Space Science Missions have Unique Solar Array Needs

SOA Solar Cells & Arrays-Overview

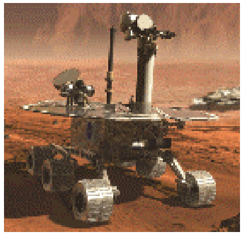
- Solar Cells
  - High efficiency Silicon and Multi Junction Solar Cells are presently being used in many space missions

Cell Type	Efficiency
High Efficiency Si Cells	16 %
Multi Junction Solar Cells	26.5%

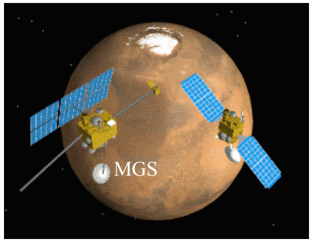


- Solar Arrays
  - Body mounted, rigid panel and flexible deployable arrays are currently being used in many spacecraft.
  - These arrays are mostly suitable for low–medium power (0.5-5 kW) applications

Array Type	Specific Power (W/kg)
Rigid Panel Array	30-40 (3 J)
Flexible Fold Out Arrays	30-50 (Si)
Concentrator Arrays	30 -60



Body-Mounted



Rigid Panel

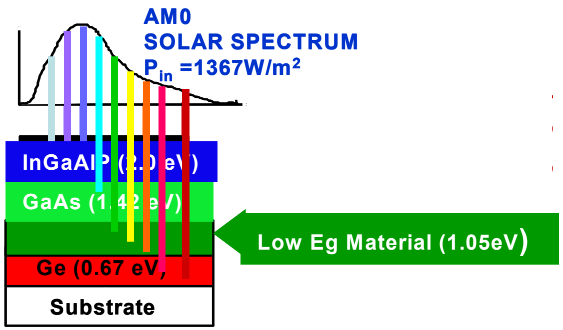
Flexible Deployable Panel

Performance of SOP Solar Cells and Arrays is Inadequate for Future Code-S Missions

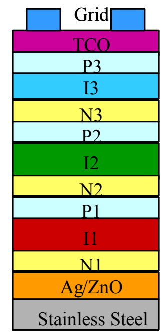
Status of Advanced Solar Cells & Arrays

- **Solar Cells**
  - Majority of the advanced solar cell technology programs are focused on improving cell efficiency and lowering the cost of the cells
  - Improved Triple Junction solar cells(28%) are in testing and qualification stage
  - Four Junction solar cells with a projected 35% efficiency are under development
  - Thin film cells are being scaled up to large sizes with >10% efficiency
  - Limited work on Mars Cells, LILT cells & high Temperature Cells
- **Solar Arrays**
  - Several low mass arrays with a projected specific power goal of 100-150 W/kg are in various stages of development (TRL 2-4)
    - These include: Ultraflex; Square Rigger; Inflatable boom deployed arrays; Advanced concentrator array

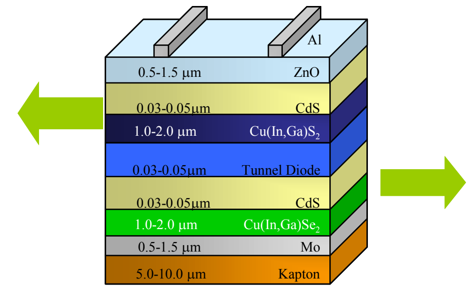
Advanced Solar Cell Technologies Under Development



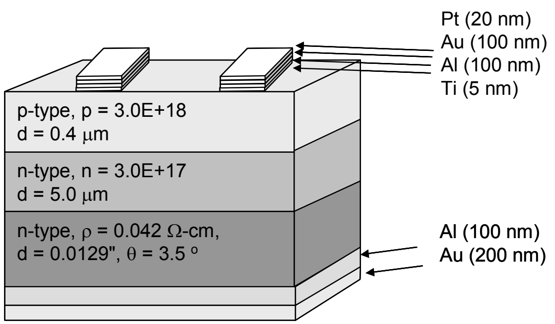
Multi Junction Crystalline Cell
Status:30%
Goal: 39%



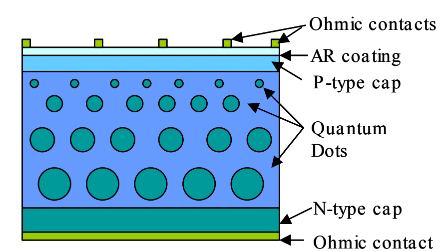
Thin Film Triple a-Si Cell
10-12%, on SS substrate
7.5 on polyimide



Thin Film $Cu(In,Ga)S_2$ Cell
Status:(9-10%)
Goal : 20%

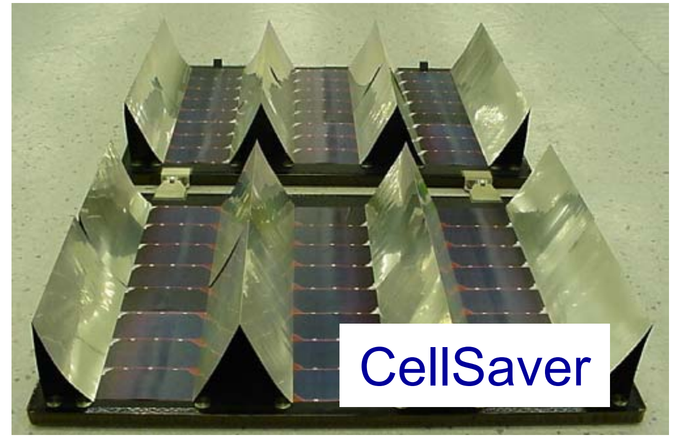


Si-C Cells:
Feasibility explored
GaInP Cells : ~ 5% at 450C,
Goal 11% at 450 C



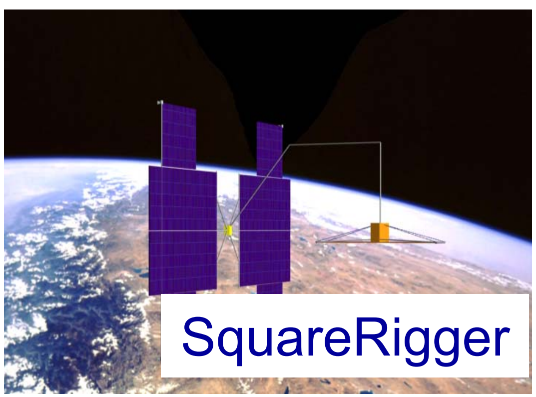
Quantum Dot Solar Cells
Status: Materials development
Goal: > 40%

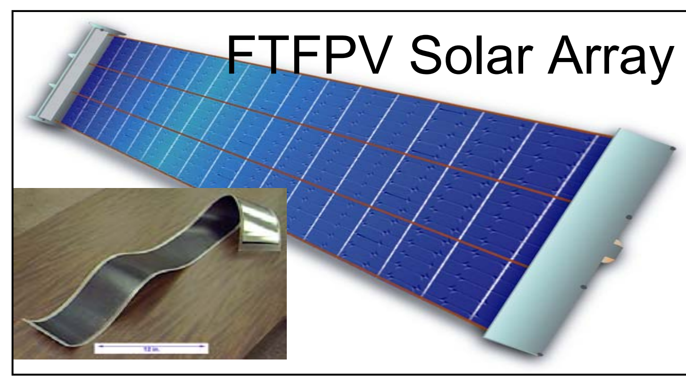
A Glimpse Into Future Array Designs



Product Performance Targets:
- Specific Power*: 150-300 W/kg
- Stowage volume*: 30-70 kW/m^3
- Status: 100 W/kg

Product Performance Targets:
- Specific Power*: 100-120 W/kg
- Stowage volume*: 10-15 kW/m^3
- Status: 60 W/kg





Product Performance Targets:
- Specific Power*: 100-300 W/kg
- Stowage volume*: 25-45 kW/m^3
- Status: Critical components fabricated

Product Performance Targets:
- Specfic power : 200- 450 W/kg (10-15%FTFPV)
- Stowage volume ~25 kW/m^3
- Status: Module development & testing, in progress

Summary of Recommendations

Recommendations :

- Develop advanced cells (high efficiency cells, LILT cells, Mars Cells, high temperature cells) .
  - Driving Missions: Outer Planet & Comet/Asteroid SEP Missions, Mars Surface Missions,SEC Near Sun missions, Earth & Mars Orbital Missions
  - Partner with AFRL to develop high efficiency solar cells and thin film cells
- Develop advanced arrays(high power & low mass arrays, long life Mars arrays, high temperature arrays).
  - Driving Missions: Outer Planet & Comet/Asteroid SEP missions, Mars Surface Missions,SEC Near Sun missions, Earth & Mars Orbital Missions
- Need to space qualify high power arrays (80 kW) for Solar Electric Propulsion missions (beyond NMP ST-8, 7 kW).

Performance Parameter Targets - Cells

Mission	Cell Type	Parameter	2003	2006	2010	2015
SSE SEP Missions	**High Efficiency Cells**	Efficiency at 1 AU	27	30	35	40
	LILT-Resistant Cells	Efficiency at 3-5 AU	30	35	40	45
	Thin-Film Cells	Efficiency (large scale)	5	10	15	20
Mars Surface Missions	**Mars Optimized Cells**	Efficiency On Mars	24	29	34	38
SEC Near-Sun Missions	**High Solar Flux Cells**	Solar Flux (suns)	8	11	25	35

Performance Parameter Targets - Arrays

Missions	Capabilities	Parameter	2003	2006	2010	2015
SSE SEP Missions	**High Power, Low Mass, Lower Cost Arrays**	Array Power (kW) at 1 AU	3	7	40	>40
		Specific Power @ 1 AU (W/kg)	60	175	225	300
		Array Cost ($M/kW)	1	0.9	0.7	0.4
Mars Surface Missions	**Arrays with Mars Cells**	Power Density (W/m^2)	130	160	175	190
	Array Dust Mitigation	Operating Life (Sols)	100	200	670	1000
SEC Near-Sun Missions	**High Solar Flux Arrays**	Solar Flux (suns)	8	11	25	35

Assessment of Energy Storage Technologies

Energy Storage Review Team

NASA/JPL

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- Subbarao Surampudi
- Gerald Halpert, Sec'y
- Donald Rapp

NASA/GRC

- Michelle Manzo
- Ken Burke
- Fred Wolff

NASA/GSFC

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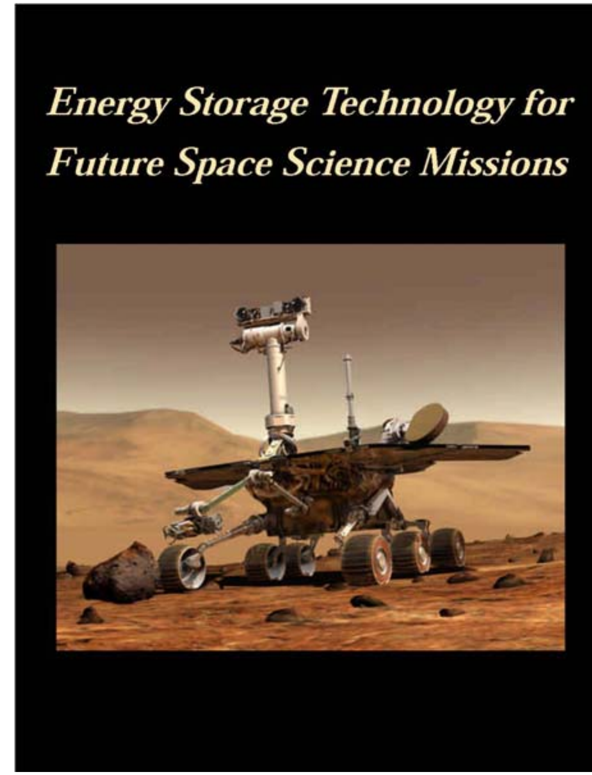
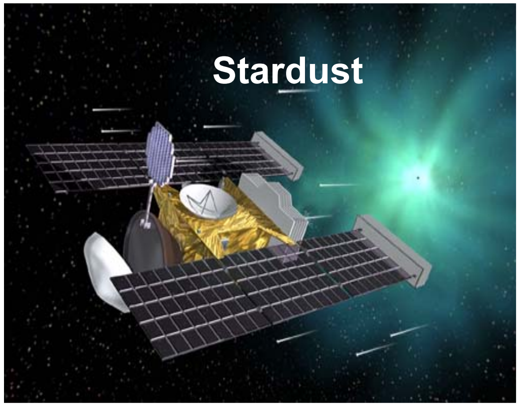
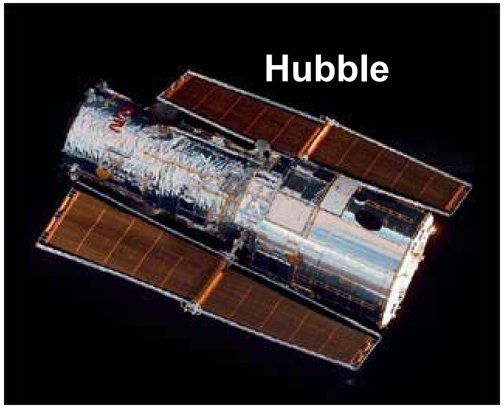
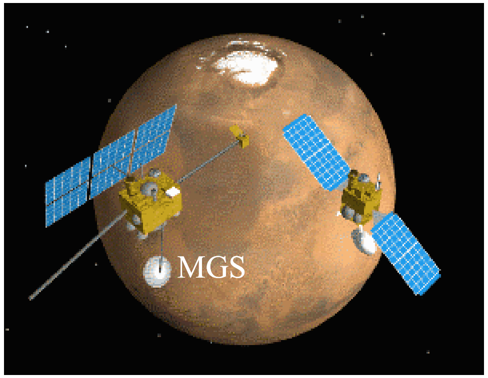


Energy Storage Systems: Past Applications

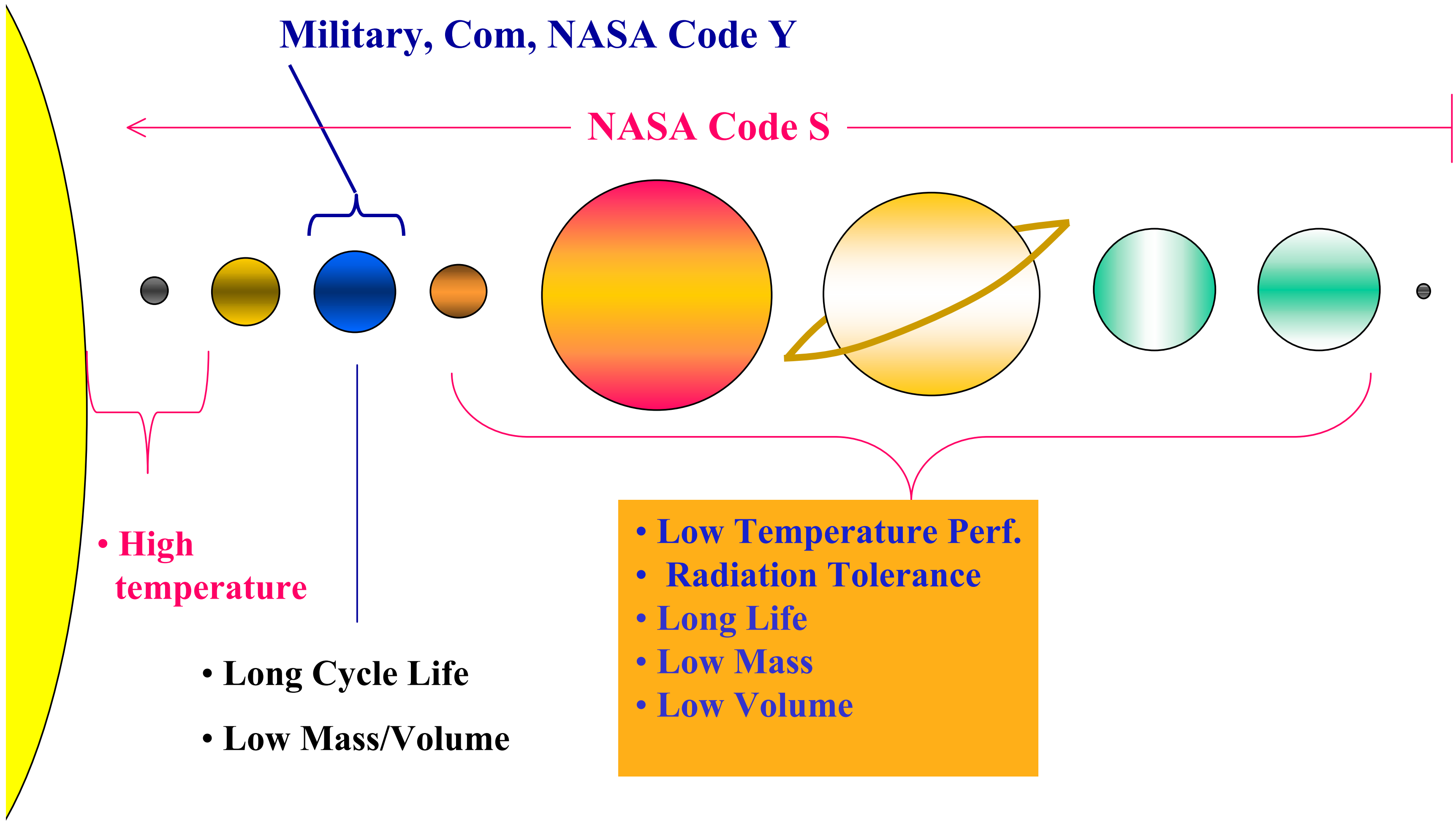






Energy storage systems have been used in 99% of the robotic space missions launched since 1960

Energy Storage Needs of Code S Missions



Energy Storage Technology Needs of Next Decadal SSE Missions

Mission Type	Mission	Critical Performance Needs	Energy Storage Tech. Needed	Benefits
Outer planetary landers/ probes (Battery powered)	•JIMO Lander •Europa Lander •Neptune probes •Giant planet atmospheric deep probes	• Low temp operation (< -100°C) • Long life (> 10 years) • Radiation resistance (5-20 Mrads) • Low mass & volume	Primary	Enabling
Outer planetary landers/ probes (RPS powered)	•JIMO Lander •Europa Lander •Neptune probes	•Long life (> 10 years) • Radiation resistance (5-20 Mrads) • Low mass & volume	Rechargeable	Enabling/ Enhancing
Inner planetary landers	•Venus sample return	• High temp. Operation (475°C) • Low mass & volume	Primary	Enabling
Outer planetary orbiters/fly-by RPS powered	•JIMO •Neptune/Triton	• Long life (> 20 years) • Radiation resistance (5-20 M Rads)	Rechargeable	Enhancing

- **Ultra low temperature, long life & radiation resistant primary batteries for outer planetary probes**
- **Long life & radiation tolerant rechargeable batteries for outer planetary orbiter /fly-by missions**
- **High temperature primary batteries for inner planetary probes**

Energy Storage Technology Needs of Next Decadal Mars Missions

Mission Type	Mission	Needs*	Energy Storage Type	Benefits
Orbiters	Mars Telecom	•Long cycle life (30K @ 30% DoD) •Low mass & volume	Rechargeable	Enhancing
Solar Powered Landers & Rovers	• MER follow-ons • Mars Sample Return	•Low mass (>120 Wh/kg) • Low temp. Operation (-60^{o}C)	Rechargeable	Enabling/ Enhancing
RPS Powered Rovers	MSL follow on	•Long life •Radiation tolerance	Rechargeable	Enhancing
Sensor Networks	Scouts	•Low temp. (-80^{o}C) operational capability •Low mass and volume	Primary	Enabling

- **Long cycle life & high specific energy rechargeable batteries for Mars orbiters**
- **High specific energy and low temperature, rechargeable batteries for solar powered landers/rovers**
- **Low temperature primary batteries for Mars surface probes/sensor networks**

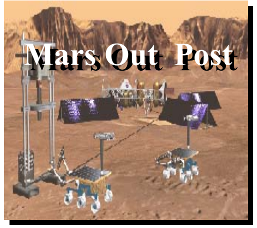
Decadal Energy Storage Technology Needs of SEC Missions

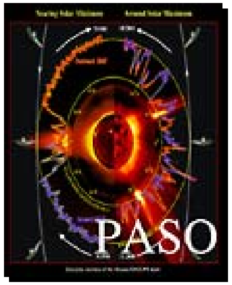
Program	**Mission Type**	**Missions**	Capability Need
SEC Program	Missions to Inner Planets & Sun	PASO, Sentinel, Solar	High Temperature Primary Batteries
	Outer Planetary Missions	Neptune Orbiter	Long Life, Low Mass, Radiation Resistance Rechargeable Batteries

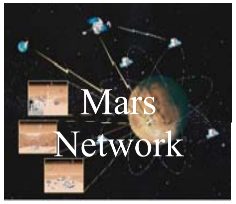
- **Long life & radiation tolerant rechargeable batteries outer planetary orbiter /fly-by missions**
- **High temperature primary batteries for inner planetary missions**

Summary of Energy Storage Technology Needs of NASA Code S Missions

1. Low temperature primary(<-100^{o}C) and rechargeable (<-60^{o}C) batteries for planetary probes and Mars surface missions
2. High temperature batteries (> 475 ^{0} C) for inner planetary missions
3. Long calendar life (>15 years), high specific energy (>120 Wh/kg) & radiation tolerant rechargeable batteries for outer planetary missions
4. Long cycle life (>30,000 cycles) and high specific energy (>120 Wh/kg) rechargeable batteries for Mars and earth orbital SEC, SEU & origins missions
5. High specific energy primary batteries (>500 Wh/kg) for comet/asteroid probes

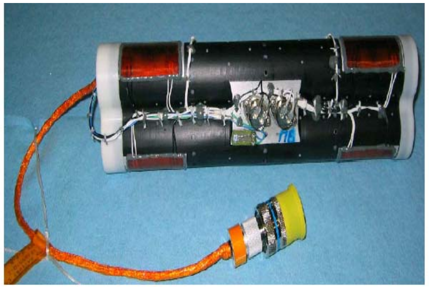






SOP Aerospace Batteries

Primary Batteries



Li-SO_2 MER
Battery

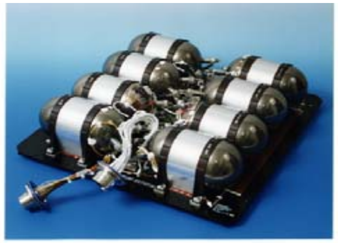
Li-$SOCl_2$ Pathfinder
Lander Battery

Rechargeable Batteries

Ag-Zn Battery

MPF Lander

Standard Ni-Cd
Solar Max
Battery



CPV
Ni-H_2Battery
Odyssey 2

Li-Ion
Battery
MER Rover

Characteristics of SOP Primary Batteries

Type	Application	Mission	Specific Energy, Wh/kg (b)	Energy Density, Wh/l (b)	Operating Temp. Range, °C	Mission Life (yrs)	Issues
Li-SO_2	Cell		238	375	-40 to 70	<10	Voltage Delay
	Battery	Galileo Probe Genesis SRC MER Lander Stardust SRC	90-150	130-180	-20 to 60	9	
Li-$SOCl_2$	Cell		390	878	-30 to- 60	>5	Severe voltage delay
	Battery	Sojourner Deep Impact DS-2 Centaur Launch batteries	200-250	380-500	-20 to 30	< 5	
Li-CF_x	Cell		614	1051	-20 to 60		Poor power capability

Limitations

- Moderate specific energy (100-250 Wh/kg)
- Limited operating temp range (-40 C to 70°C)
- Radiation tolerance poorly understood
- Voltage delay

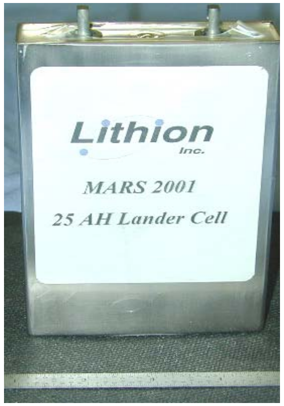
Characteristics SOP Rechargeable Batteries

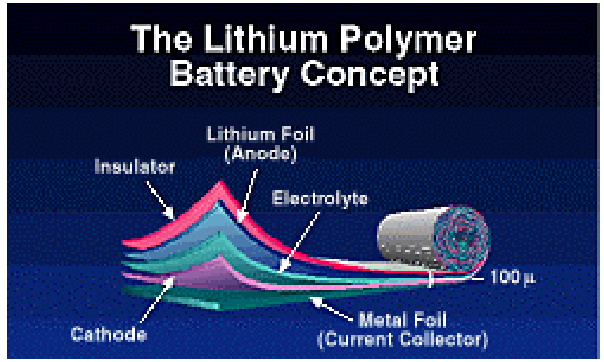
Technology	Mission	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Design life, Years	Cycle life	Issues
Ag-Zn	Pathfinder Lander	100	191	-20 t0 25	2	100	Electrolyte Leakage Limited Life
Ni-Cd	Landsat, TOPEX	34	53	-10 to 25	3	25-40K	Heavy Poor Low Temp. Perf.
Super Ni -Cd	Sampex Battery, Image	28-33	70	-10 to 30	5	58K	Heavy Poor Low Temp. Perf
IPV Ni -H_2	Space Station, HST, Landsat 7	8-24	10	-10 to 30	6.5	>60K	Heavy, Bulky Poor Low Temp. Perf
CPV Ni-H_2	Odyssey, Mars 98 MGS, EOS Terra Stardust, MRO	30-35	20-40	-5 to 10	10 to 14	50 K	Heavy, Bulky Poor Low Temp. Perf
SPV Ni -H_2	Clementine, Iridium	53-54	70-78	-10 to 30	10	<30 K	Heavy Poor Low Temp. Perf
Li-Ion	MER-Rover	90	250	-20to 30	1	>500	Limited Life

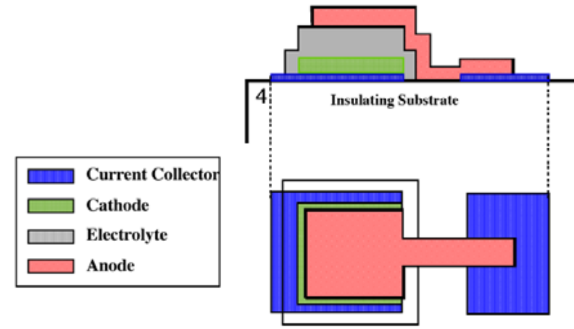
Limitations of Ni-Cd & Ni-H2 batteries:

- Heavy and bulky
- Limited operating temp range (-10°C to 30°C)
- Radiation tolerance poorly understood.

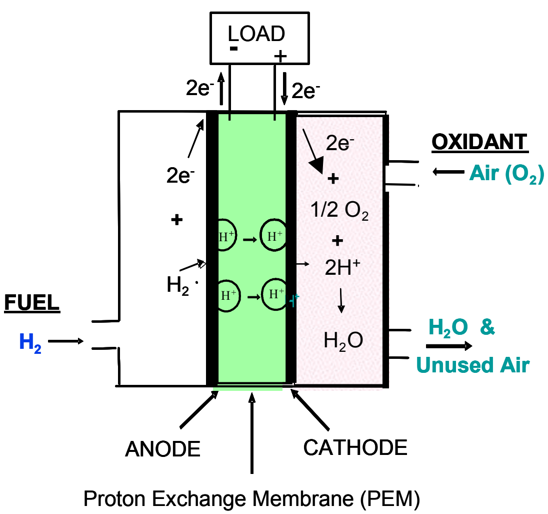
Adv. Energy Storage Technologies Under Development



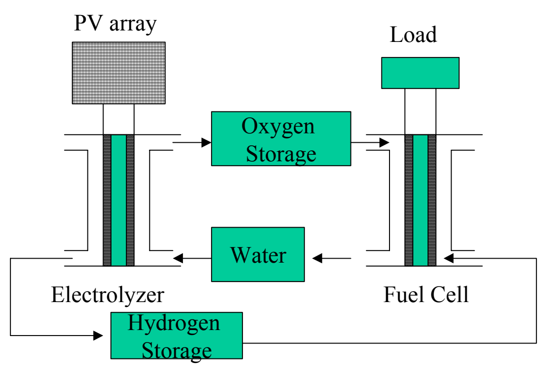




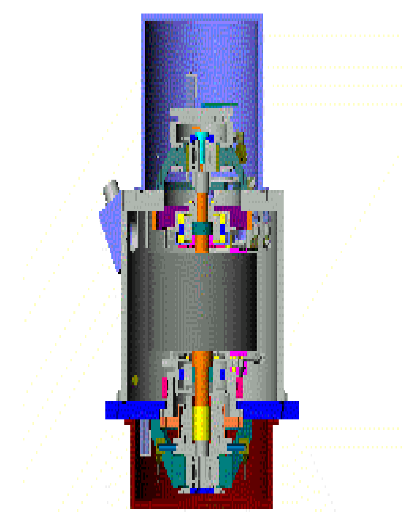
Li solid state Batteries



PEM Fuel Cells



Regenerative Fuel Cells

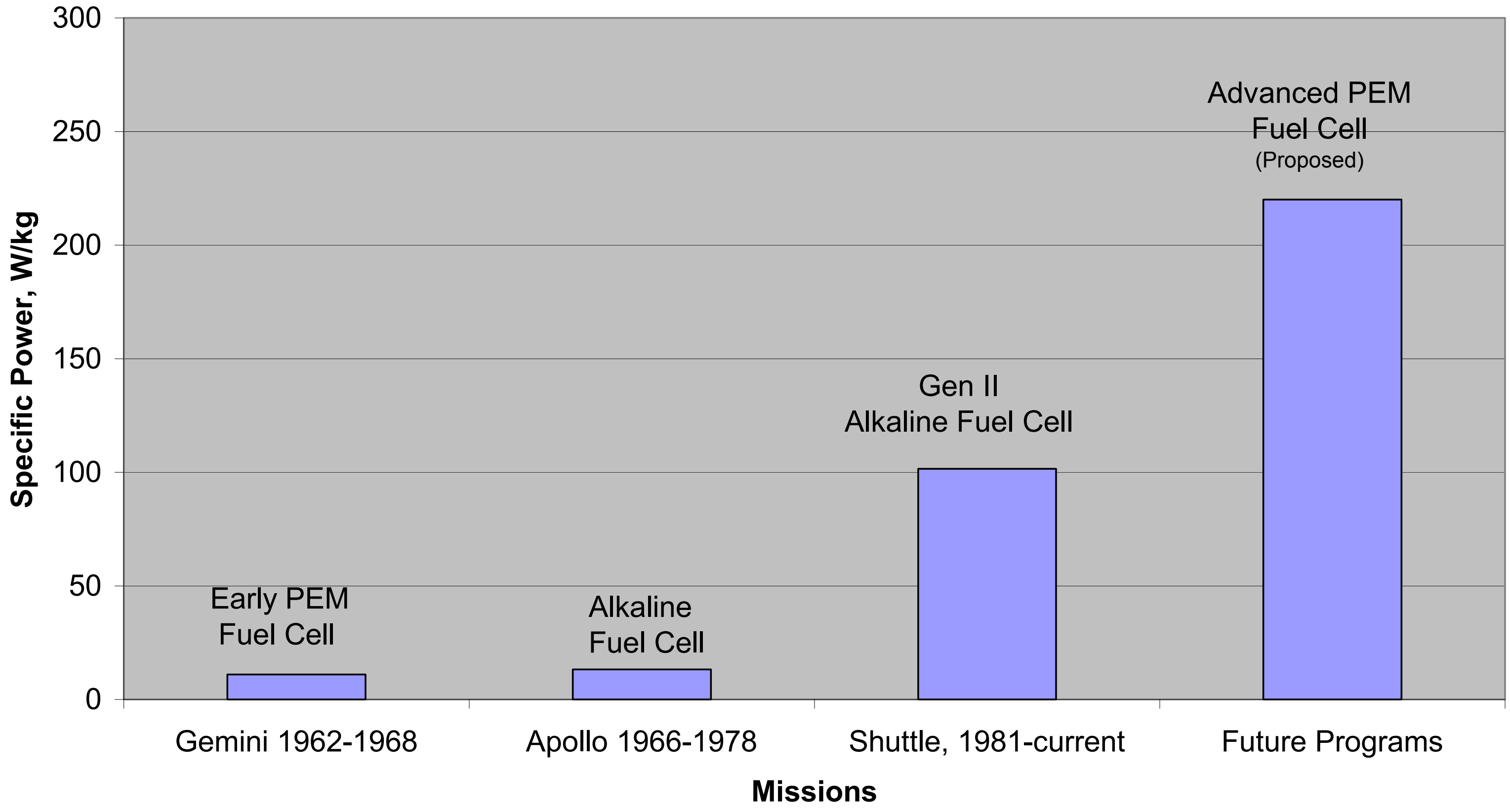


Flywheel System Schematic

Characteristics of Advanced Rechargeable Batteries

Characteristic	SOP Ni-H_2	Li-Ion with liquid electrolyte	Li-Solid Polymer Electrolyte*	Li-Solid Inorganic Electrolyte*
Technology Readiness Level	10	5-9	3	1-2
Specific energy (Wh/kg)	30-40	100-150	>200	> 200
Energy density (Wh/l)	40-50	200-300	300-450	> 300
Cycle life	60, 000	1500	1500	>10,000
	(at 30% DOD)	(at 100% DOD)	(at 100% DOD)	at 100% DOD
Operating temperature	-5-30 C	-60 to 80 C	0-80 C	0-80 C
Self discharge rate		1% / month	0.25% / month	0.1% month
Shape factor /packing eff	Poor	Good	Excellent	Excellent

Characteristics of Fuel Cells



Recommendations

- Develop advanced primary and rechargeable battery technologies to enable future space science missions
  - High specific energy and long-life rechargeable batteries for Mars and earth orbital missions (long cycle life) and outer planetary missions
  - Low temperature rechargeable Li-Ion batteries (-80 C) to enable /enhance the capabilities of solar powered *in-situ* exploration missions
  - Low temperature lithium primary batteries (< -100 C) to enable/enhance the capabilities of planetary probes and *in-situ exploration* missions .
- Conduct a study to evaluate competing high temperature rechargeable and primary battery technologies to determine their value in enabling high-performance future missions (surface and atmospheric) to Venus
- Establish a test and validation program to demonstrate the electrical performance, life capabilities, and identify problems of advanced energy storage technologies.
- Work with AFRL and other DoD agencies to transition advanced energy storage technologies to industry for technology maturation and mission insertion.

Long Life Rechargeable Battery Performance Targets

	Ni-H2	Lithium Technology		
Characteristics	Present State of Practice	Present State of Practice	Goal 5 years	Goal 10 years
Specific Energy (Wh/kg)	30	100	120	200
Energy Density (Wh/liter)	10	200	200	400
Cycle Life at 30% DOD *	50,000	10-15,000	30,000	50,000
Calendar Life (years)	15	3	10	15

* DOD = Depth-of-discharge

Low Temperature Rechargeable Battery Performance Targets

	Lithium Ion Technology		
Characteristics	Present State-of-Practice	5 years	10 years
Specific energy at $0^{o}C$ (Wh/kg)	100	120	200
Life Time (yrs)	5 yrs	10yrs	15 yrs
Cycle Life (# of cycles) (80%DOD)	> 500	> 500	> 500
Low Temperature Performance			
Specific Energy at $-20^{o}C$	70	100	160
Specific Energy at $-40^{o}C$	40	80	140
Specific Energy at $-60^{o}C$	0	65	120
Specific Energy at $-80^{o}C$	0	40	80
Discharge rate (hours)	>10	> 10	> 10

Low Temperature Primary Battery Performance Targets

Primary Energy Storage Characteristics	Present State of Practice	Goal (5 years)	Goal (10 years)
Specific Energy at $0^{o}C$ (Wh/kg)	250	400	600
Specific Energy at $-40^{o}C$ (Wh/kg)	100	200	300
Specific energy at $-80^{o}C$ (Wh/kg)	50	100	200
Discharge rate (hrs)	> 20	> 20	> 20

Acknowledgments

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